Met Office

Remodelling the Irish national onshore and offshore wind atlas

Forecasting Research
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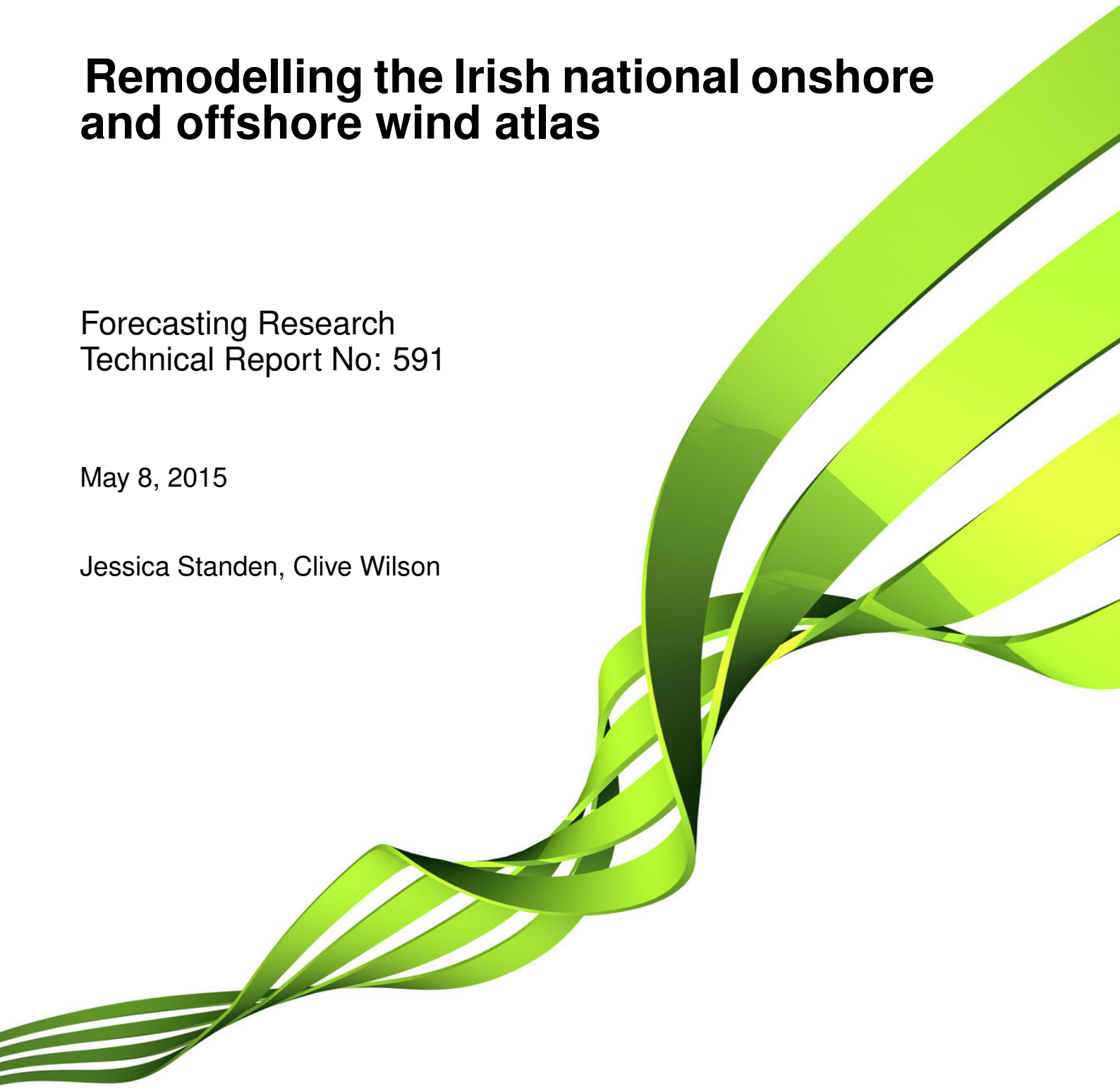

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1 Introduction

The Met Office was awarded a contract by the Sustainable Energy Authority of Ireland (SEAI) following a competitive tender process, to produce an updated Irish national onshore and offshore wind atlas. This technical report is a summary of the project report delivered to SEAI in 2013 as part of the tender. It documents the methods used and contains a discussion of some of the results.

The Met Office was only contracted for *Lot 1: The Modelling Methodology*. The approach taken was based on adapting and using some of the methods used in the Met Office's Virtual Met Mast™ (VMM), a site specific tool designed to provide an initial accurate assessment of the long term wind profile prior to installing a real mast.

2 Background

Despite Ireland having one of the best potential onshore and offshore wind resources, Ireland currently imports 89% of its energy. As well as it being a Government policy objective to exploit Ireland's renewable energy resources to both reduce pollutant emissions and improve national energy security, Ireland also has an obligation to produce 16% of its energy from renewable sources by 2020. It is likely that a large proportion of this 16% target will need to be satisfied by wind power.

In 2002/3 a wind-mapping project conducted by ESBI International, with TrueWind Solutions under a contract with Sustainable Energy Ireland produced the previous wind atlas of Ireland. This consisted of files of mean wind speed and power at three heights (50m, 75m and 100m above ground level (agl)) on a 200m grid covering Ireland and up to a distance of 20km off the Irish coast on a 400m grid. Further information on the project is contained in the project report (Brower et al. 2003).

The project documented in this report was designed to remodel the previous wind atlas discussed above. Previous wind atlases have been used to inform the strategic development of Ireland's wind resource, being used by a wide range of users, from state bodies and wind project developers to researchers and home and business owners.

For this project, remodelling the Irish national onshore and offshore wind atlas, the data supplied have been produced at 8 requested heights, **20m, 30m, 40m, 50m, 75m, 100m, 125m and 150m agl**. In addition to these 8 heights, the data were also produced at 10m agl for internal use and validation purposes.

The wind atlas has been produced over the domain specified by SEAI (Figure 1). The offshore areas required were supplied to the Met Office from SEAI, however, it was necessary to also add in the land area to this and transform the area onto the Irish Transverse Mercator (ITM) projection grid.

The final agreed upon deliverables between the Met Office and SEAI are outlined below.

1. *Report on planned execution of project.*

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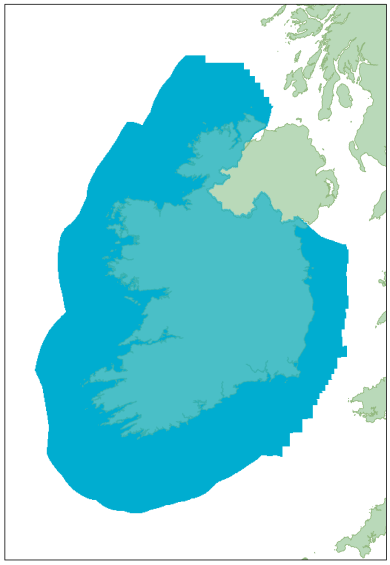

Figure 1: **Output domain (blue)** - on the ITM projection grid

2. *A multi-year average gridded 100m resolution dataset of mean wind speed and the mean frequency of wind direction in twelve 30 degree bins. The averaging period will be 10 years (2001-2010).*

3. *A gridded 100m resolution dataset of mean wind speed for each month averaged over the 10-year period.*

4. *A gridded 100m resolution dataset of mean wind speed for each hour of day averaged over the 10-year period.*

5. *A gridded 1km resolution dataset of Weibull parameters and data required to generate wind roses, in twelve 30 degree bins, over the 10-year period.*

6. *A representative 1-year time series of 1km-gridded wind speed and direction, plus correction formulae which can be used to post-process this time series onto the 100m grid.*

7. *Validation of the VMM post-processing approach on a site specific basis, using available wind data from Irish synoptic observing sites, existing wind farms in Ireland and gridded data. This will provide estimates of uncertainty levels at a wide range of sites, from offshore and flat terrain, to complex terrain, which can then be used to estimate uncertainty on the 100m grid.*

8. *Final report on the new wind atlas and results of the validation process. A full technical description of the methods and user guide.*

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3 Method

The approach used to remodel the Irish national onshore and offshore wind atlas is based on the methods used in the VMM, a site screening tool designed to assess the feasibility of potential wind farm sites. It provides climatological wind information for locations both onshore and offshore. This approach relies on the use of past high resolution (4km) data from the Met Office numerical weather prediction (NWP) models. Corrections are applied to this data to account for the local site complexity. Further information on this process can be seen in a paper in preparation Standen et al. (2015).

To produce the Irish wind atlas these corrections are applied at each point on a 1km grid, producing gridded 1km corrected wind speed and direction data. This 1km data has then been time processed to produce monthly fields, which have then been further downscaled onto a 100m grid.

3.1 Initial Data

The Met Office Unified Model (MetUM) is an atmospheric model that was designed to be 'seamless' from its inception. This means that different configurations of the same model are used across all time and space scales, being used operationally for both global and limited area NWP as well as for climate research (Cullen 1993). The atmospheric model is non-hydrostatic, fully compressible, with semi-Lagrangian advection and semi-implicit time stepping (Davies et al. 2005). In the MetUM there are a number of sub-grid scale processes represented, including convection, boundary layer turbulence, radiation, cloud, microphysics and orographic drag.

The model also uses ancillary files to represent the surface characteristics, such as orography, vegetation and soil type and also certain atmospheric conditions such as ozone concentration and aerosol emissions. The orography used in the highest resolution model used for this project comes from the DTED[1] dataset. The MetUM uses 9 tiles to represent the different vegetation types and fractions of each of these 9 tiles are used at each point in the domain. For the highest resolution model used for this project these fractions are generated from the ITE[2] land use dataset combined with the IGBP[3] land use dataset where the ITE land use dataset is not available (e.g. over Ireland).

Reanalysis datasets are often used as the base data for producing a wind atlas. For the production of this wind atlas ERA-Interim reanalyses were used. ERA-Interim is a global reanalysis dataset produced by European Centre for Medium-Range Weather Forecasts (ECMWF) providing three-dimensional estimates of meteorological variables every 6 hours since 1st January 1979 and is being updated on a monthly basis. ERA-Interim used 4D-Var data assimilation to include all of the available observations over the period. Further information on ERA-Interim can be found in Dee et al. (2011).

[1] The National Imagery and Mapping Agency (NIMA, formerly Defense Mapping Agency (DMA))'s Digital Terrain Elevation Data set.

[2] Land use dataset produced by the Centre for Ecology and Hydrology (CEH), formerly known as the Institute of Terrestrial Ecology.

[3] Land use dataset produced by the International Geosphere and Biosphere Programme.

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Previous to this project, the MetUM was used to rerun 10-years of forecasts (2001-2010). This was run as a nested configuration, where ERA-Interim analyses[4] were used to initialise an N216 (∼60km horizontal resolution at mid-latitudes), 50 vertical-level global model. This provided the initial and lateral boundary conditions for a 38-level 12km Western European model. In turn this drove three 70-level 4km domains, one of which was centred over the UK and Ireland. The Western European (green) and UK (red) domains are shown in Figure 2.

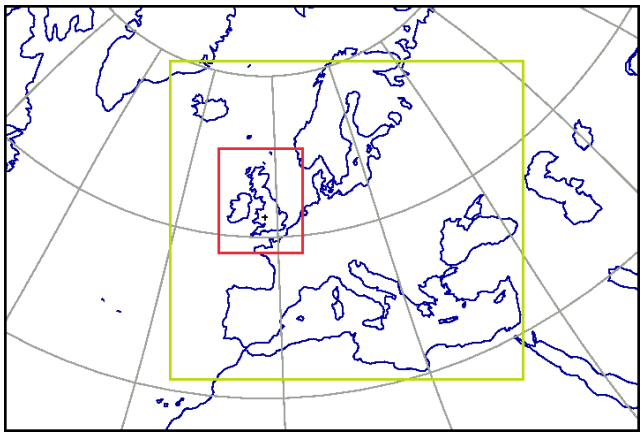

Figure 2: **Western European (green) and UK (red) domains**

This set up was run every 48 hours starting from the 00Z ERA-Interim analyses; a 6 hour spin-up was allowed for the global model to adjust from the ERA-Interim reanalysis, before starting the Western European model, and a further 3 hour spin-up period was allowed before starting the 48-hour 4km resolution simulations. This has resulted in a consistent and continuous 4km resolution 10 year dataset. The 4km models were run with a 100-second time step, but only hourly data were retained in the dataset.

The 4km UK configuration of the MetUM discussed above was identical to the operational configuration used for forecasting for the UK (the UK4 model) at that time. The UK4 model is highly tuned and has been refined over several years, being verified daily against a range of observations. The model has 70 vertical levels, with 6 levels below 150m (2.5m, 13.33m, 33.33m, 60m, 93.33m and 133.33m). The spacing between the levels is non-uniform, with the finest resolution in the boundary layer, becoming progressively coarser with height through the troposphere and stratosphere. The model levels below 2000m can be seen pictorially in Figure 3.

The 4km hourly model level wind components from the UK model, which covers the UK and Ireland, forecast dataset are used as the base data for the Irish wind atlas.

The previous Irish wind atlas was produced by only simulating 366 days selected from a 15-year period, where the days were chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample (Brower et al. 2003). Conversely, the remodelled Irish wind atlas has been produced by simulating all 3652 days in the full 10-year period

[4]The ERA-Interim 3D fields (60 vertical levels) used were specific humidity, temperature, U velocity and V velocity and the single level fields surface pressure, skin temperature, geopotential, land-sea mask and snow depth.

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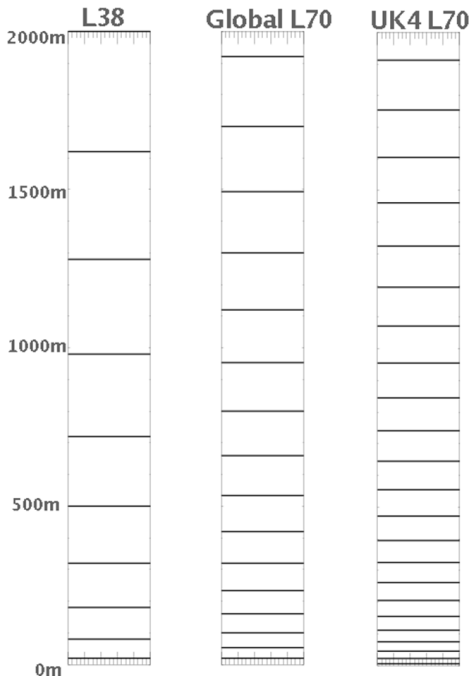

Figure 3: **Model Levels Used in MetUM**

(2001-2010) that the wind atlas is designed to represent.

3.2 Corrections

The 4km wind components on the 70 model levels from this dataset are then downscaled onto a 1km grid using horizontal bilinear interpolation and then vertically interpolated to the 8 requested heights (20m, 30m, 40m, 50m, 75m, 100m, 125m and 150m) by assuming a logarithmic profile between model levels. A scaled roughness correction is then applied to adjust the winds over significant orography (Section 3.2.1) and following this, an adjustment for local height difference on the 1km grid using a wind direction dependent Mason and King (1985) linear model with 4 wind directions (Section 3.2.2).

This produces hourly fully corrected wind speed and direction files on a 1km resolution grid at the requested heights. These are then averaged and time processed to produce monthly fields, which are then downscaled onto a 100m resolution grid with an extension to the wind direction dependent Mason and King (1985) linear model previously applied (Section 3.2.3).

A plot of the 1km orography used in these corrections can be seen in Figure 4. In addition to this a 100m orographic data set is also used in the linear correction.

3.2.1 Scaled Roughness Correction

The MetUM includes physical parametrisations for the effects of sub-grid orography, including an orographic drag scheme which is used to represent the turbulent form drag exerted on the synoptic-scale flow in the boundary layer by this unresolved orography. This has a beneficial impact in

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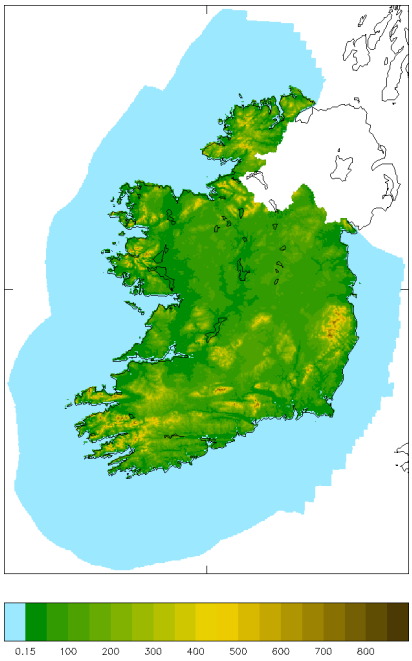

Figure 4: **Plot of the orographic height (m)** - on the 1km rotated pole grid

the NWP performance due to its positive effect on the synoptic-scale flow; however, it results in unrealistically low near-surface wind speeds over complex orography.

An example of this unresolved orography can be seen in Figure 5, which shows a horizontal cross section from (53.06N,-7.00E) to (53.06N,-6.00E) of the 4km orography used in the model with the corresponding cross section from the 100m DTED orographic dataset. This demonstrates the level of sub-grid variation that there can be.

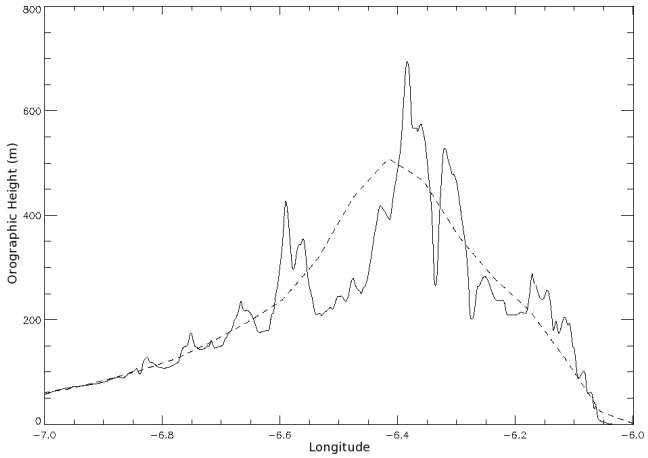

Figure 5: **Orographic Height for the 4km model orography (dashed) and 100m orography dataset (solid)** - cross section from (53.06,-7.00) to (53.06,-6.00)

Figure 6 shows where this horizontal cross section was taken and the difference between the 4km model orography (6(a)), the 1km orography used in the scaled roughness correction (6(b)) and the 100m orographic dataset used in the linear correction (6(c)).

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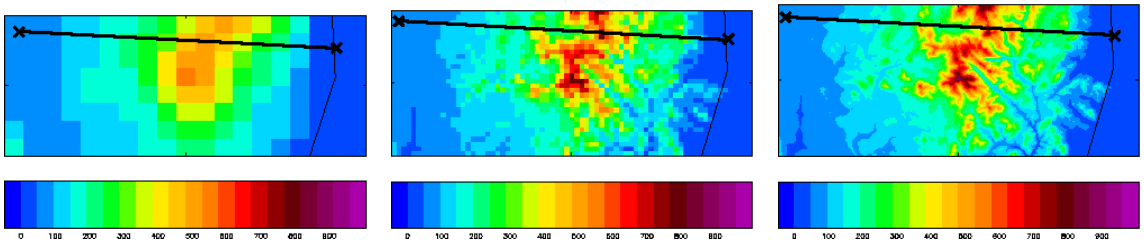

(a) 4km (b) 1km (c) 100m

Figure 6: **Orographic height (m)**

The roughness correction applied during the remodelling of the Irish national onshore and offshore wind atlas is designed to correct for these artificially low near surface winds over complex orography. It was developed for use in the VMM and is based on Howard and Clark (2007). This correction is only applied at locations where the height that the winds are being estimated is below a reference height. The reference height is defined to be the height below which the orographic roughness parametrisation will significantly affect the wind profile. It is calculated using the silhouette area per unit area (A/S) and the average peak-to-trough amplitude ($H/2$) of the sub-grid orography. The reference height z_{ref} is defined as:

$$z_{ref} = ak^{-1} \tag{1}$$

where a is a tunable parameter and k is the local wavenumber. Due to the possibility of spuriously high values of z_{ref} over modest terrain, if A/S is sufficiently small relative to $H/2$, a modification has been made to the value of k compared to that used in Howard and Clark (2007).

$$k = \begin{cases} \frac{\pi(A/S)}{(H/2)} & (H/2) \geq (H/2)_{min} \\ \frac{\pi(A/S)}{(H/2)_{min}} & (H/2) < (H/2)_{min} \end{cases} \tag{2}$$

$$\frac{1}{\Delta x_{max}} \leq \frac{(A/S)}{(H/2)} \leq \frac{1}{\Delta x_{min}} \tag{3}$$

where $(H/2)_{min}$ is set to 1m and Δx_{min} and Δx_{max} are set to 500m and 4km respectively.

In the VMM and hence in this project the tunable parameter a is set to be:

$$a = \begin{cases} -\ln\alpha + \ln(kH/2) & \ln(kH/2) > \beta \\ -\ln\alpha + \beta & \ln(kH/2) \leq \beta \end{cases} \tag{4}$$

with $\beta = -4$ and $\alpha = 0.12$. The value of α was tuned in the VMM as a result of tests compared with observations over the UK.

The roughness correction is only applied at locations on the grid where the height the wind atlas is being produced (z_{hub}) is below the reference height for that location. When the correction is applied a neutral logarithmic wind profile is assumed below z_{ref} and the roughness corrected wind

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speed (U_{rc}) is given by:

$$U_{rc}\left(z_{hub}\right) = \frac{u_*}{\kappa} \ln\left[\left(z_{hub} - d\right)/z_0\right] = U\left(z_{ref}\right) \frac{\ln\left[\left(z_{hub} - d\right)/z_0\right]}{\ln\left[\left(z_{ref} - d\right)/z_0\right]} \tag{5}$$

where u_* is the friction velocity, κ is the von Kármán constant and z_0 and d are the local vegetative roughness length and displacement height, respectively. z_0 and d are calculated from the Corine land use data set (European Environment Agency 2007), and more information on how these were defined can be seen in Appendix A. The definition of U_{rc} in Equation 5 has been slightly modified compared to that used in Section 3.2 of Howard and Clark (2007) to take into consideration the displacement height.

The correct phase of the diurnal cycle of wind speeds can be lost if the Howard and Clark (2007) correction is applied simply. This is because during the middle of the day with reduced stability and greater vertical mixing results in upper layers exchanging momentum with lower layers. Therefore at lower elevations the diurnal cycle typically shows enhanced wind speeds during daylight around midday, whilst in contrast upper elevations the reverse occurs. Using the elevated winds at the reference height $U(z_{ref})$ to correct each hour will thus reverse the diurnal cycle at lower elevations. To eliminate this, mean correction factors from the average ratio of winds speeds before and after the Howard and Clark (2007) correction are applied to the uncorrected winds, which thus retain their original diurnal phase variation. The average factors are derived for each month.

3.2.2 Linear Model Correction

A height correction is also defined in Howard and Clark (2007). However, through testing using this in both the VMM and for wind atlas generation it was found to be less accurate than an alternative correction method to account for local height difference on the 1km grid. This is based on Model D of Mason and King (1985). The orography for a small region (6.4km square) about each 1km grid point is extracted from the 100m data set (e.g. Figure 7(a)). The orography is tapered to zero away from the central point (e.g. Figure 7(b)) and Model D is solved for each Fourier component for a number of wind directions; here we have used 4 wind sectors for economy, viz. 60, 150, 240 and 330 degrees. At each of the elevations a scaling factor is derived for each direction and at each 100m grid point (e.g. Figure 8). This is applied using the scaled wind speeds at the central (1km) grid point to produce local speed-ups and decreases. By applying these dependent on the wind direction of the 1km winds, height corrected winds are obtained.

3.2.3 Linear Model Correction Extension

The method outlined in Section 3.2.2 produces scaling factors for each of the 100m grid points in the 6.4km square region relative to the central (1km) grid point for each of the 4 wind directions, called speed-up ratios. These can be used to calculate the wind speeds in the local region from

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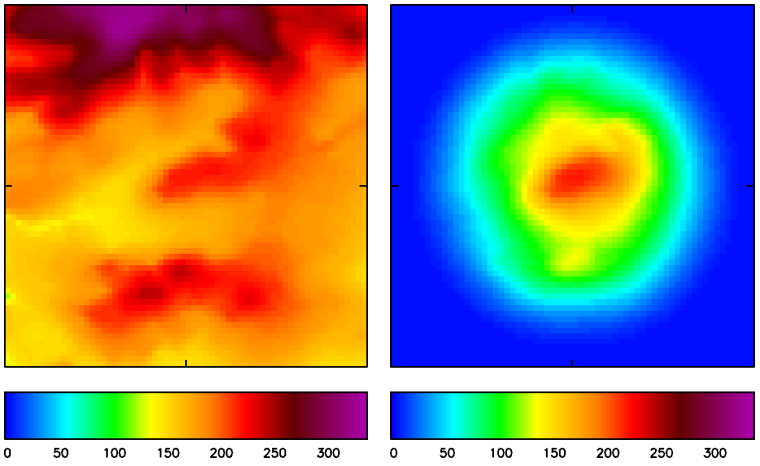

(a) Extracted Orography (b) Orography once window function applied

Figure 7: **Example orography used in the linear correction model** - for a point in south west Ireland

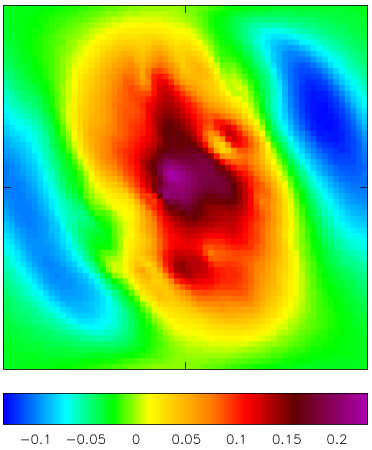

Figure 8: **Example speed-up for 240 degrees at 50m** - for a point in south west Ireland

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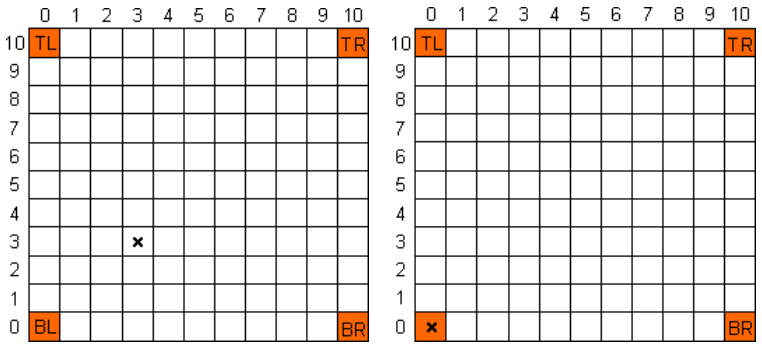
the wind speed at the central point. These have been used to downscale the winds from the 1km rotated pole grid to the 100m rotated pole grid.

In order to produce a continuous map of wind speeds special consideration was taken in the application of these speed-up ratios. It was only average files that were downscaled using this method, so it was applied using the mean wind speed for each of the 12 wind direction bins and the frequency of each of these bins, but the method would work the same for instantaneous wind speeds and wind directions, where the frequencies for all the bins would be 0 except one bin which would have a frequency of 1.

- For each point on the 100m rotated pole grid the four nearest 1km grid points were found, henceforth known as the corner points. (Figure 9)



(a) Standard selection

(b) Special selection where 100m grid point is the same as a 1km grid point

Figure 9: **Selection of four corner points on the 1km grid**

- For each of these corner points the mean wind speed and frequency of each of the four 90 degree wind direction bins used in the linear correction were calculated from the twelve 30 degree wind direction bins that the data were stored in.
- Each of the corner points' mean wind speeds were then multiplied by the speed-up ratios corresponding to the point on the 100m grid being considered for each of the four wind directions.
- These were then multiplied by the frequency of each of the four wind direction bins.
- The four wind speeds corresponding to each corner were then weighted depending on the distance of the 1km grid point from the 100m grid point. (Figure 10)
- The 16 weighted wind speeds were then summed to produce the final corrected wind speed for the 100m grid point.

This gives that the wind speed U at each 100m grid point is defined as a sum over the 4 wind directions j and the 4 surrounding 1km grid points i:

$$U = \sum_{i=1}^{4} \left(\sum_{j=1}^{4} U_i(\theta_j) \cdot s_i(\theta_j) \cdot f_i(\theta_j) \right) \cdot w_i \tag{6}$$

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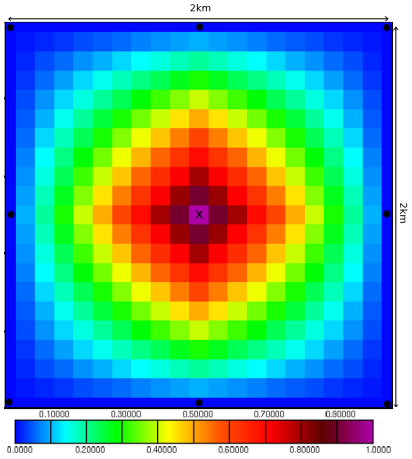

Figure 10: **The weighting of point x used**

where $U_i(\theta_j)$ is the wind speed corresponding to the wind direction θ_j at the 1km grid point i, $f_i(\theta_j)$ is the frequency of wind direction bin θ_j at the 1km grid point i, $s_i(\theta_j)$ is the speed-up ratio for the 100m grid point with respect to the 1km grid point i for the wind direction θ_j and w_i is the weight dependent on the distance of the 1km grid point i from the 100m grid point being considered.

3.3 Product Generation

In order to produce some of the final products from the data generated using the methods discussed there was some final processing to be completed. All data then needed to be put onto the ITM projection grid) and finally converted to the agreed delivery data format NetCDF.

4 Validation

The updated Wind Atlas is derived for the period 1 January 2001 to 31 December 2010. As such the 10 year means are strictly only valid for this decade. However they may be used as an indication of the likely long term mean winds. To validate the atlas with confidence a large number of independent high quality observations are ideally needed. Generally this is not the case and all current wind atlases for different countries suffer to a greater or lesser extent from a limited sampling of the "truth".

A variety of approaches were taken as part of the project to maximise the observations for Ireland available. Three different observation sets were used: (1) 10m winds from the standard meteorological synoptic networks; (2) elevated observations from meteorological masts; and (3) observations from the Small Wind Power Project. The elevated observations were from existing and proposed wind farms and were kindly supplied by the site operators. The Small Wind Power Project observations were from the period 2011-2012 so a direct comparison of hourly winds was not possible but a more qualitative comparison of mean winds was done.

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The results from the verification done as part of this project are summarised in this report, but are detailed in the full project report supplied to SEAI.

4.1 Complexity Classification

Every point on the 1km grid was categorised as either offshore, near-shore, low, medium, or high complexity based on values of A/S (silhouette area per unit area). The categories are defined as follows:

$$\text{complexity} = \begin{cases} \text{offshore}, & A/S = 0 \ \& \ d > 5km \\ \text{near-shore}, & A/S = 0 \ \& \ d \leq 5km \\ \text{low}, & 0 < A/S < 0.0075 \\ \text{medium}, & 0.0075 \leq A/S < 0.02 \\ \text{high}, & 0.02 \leq A/S \end{cases}$$

where d is the minimum distance from a land point.

Figure 11 shows the categorisation of all of the points on the 1km grid.

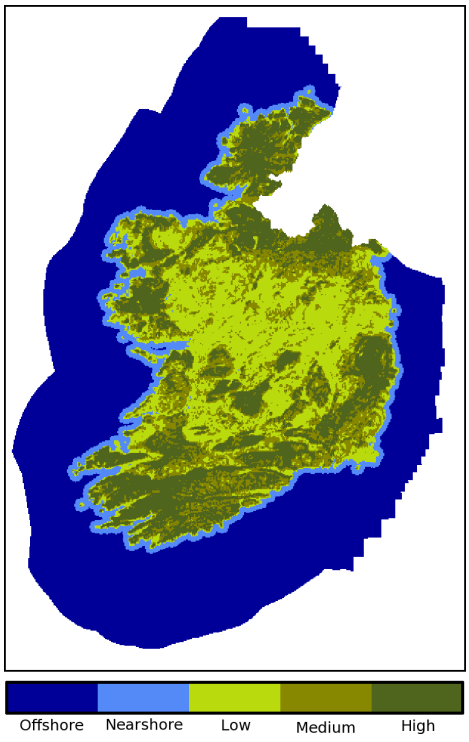

Figure 11: **Complexity categorisation on the 1km ITM projection grid**

The points are categorised based on the values of A/S as this represents the complexity of the surrounding area. For this reason the values of A/S were calculated on the 1km grid, using the values contained within the 1km grid box, for which the point is in the centre. The values of A/S used on the 100m grid were taken as the value of the nearest 1km grid point, this has been done to

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account for the true complexity of the location, which is affected by an area larger than just the grid box around the 100m grid point.

4.2 Validation Based on 10m Observations

A comparison was made between meteorological synoptic station observations and hourly wind values from the atlas for 33 stations over Ireland and Northern Ireland. These "surface" observations are nominally made or reported at a 10m elevation and use WMO standard procedures and certification. The values taken from the wind atlas were at 10m agl (not supplied to SEAI, these were produced for internal verification purposes) and from the 1km resolution hourly wind files; the wind speeds for each station were assigned using bilinear interpolation, but wind directions were from the nearest 1km grid point without interpolation. The observed and atlas winds were matched so that only concurrent times were used. Only results for Malin Head (WMO index 03980) are shown in this report.

At Malin Head, (Figure 12), the agreement between the wind atlas and observed winds each hour is of good quality and similar to standard VMM results over the UK. The correlation coefficient $R^2 = 0.59$. Observed and modelled wind roses are also in reasonably good agreement, although the model is deficient in the southerly band it is slightly over populated in the WSW and SSE bands (Figure 13).

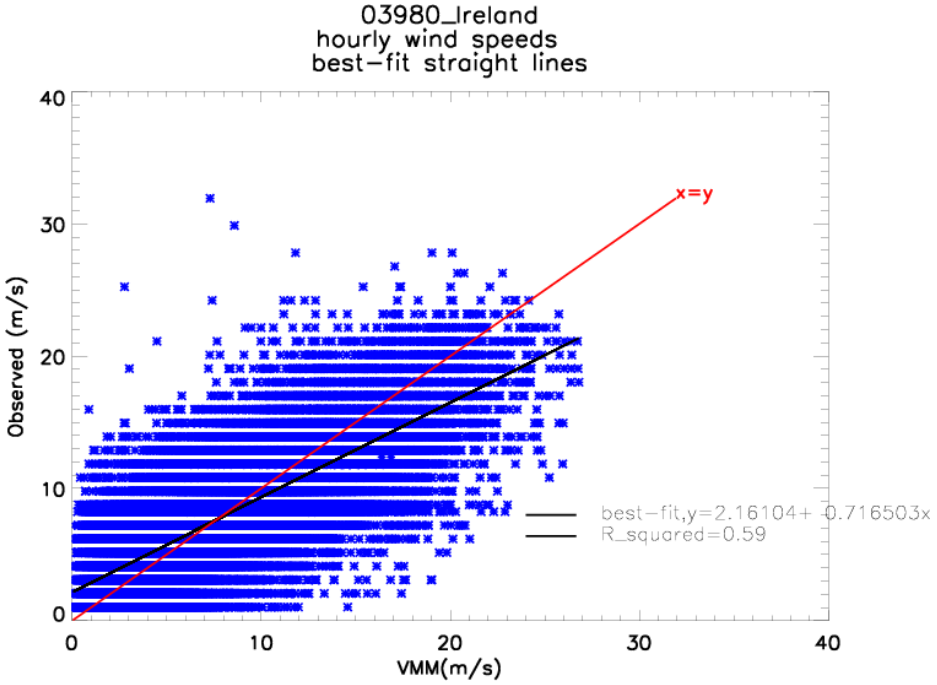

Figure 12: **Hourly wind speeds for the observed and wind atlas at Malin Head at 10m agl**

On a monthly time scale (Figure 14) the observed and modelled winds correlate very well and overall the modelled bias is practically zero with the atlas mean wind agreeing with the mean of the observations of 7.7 ms^{-1}, to a precision of 0.1 ms^{-1}.

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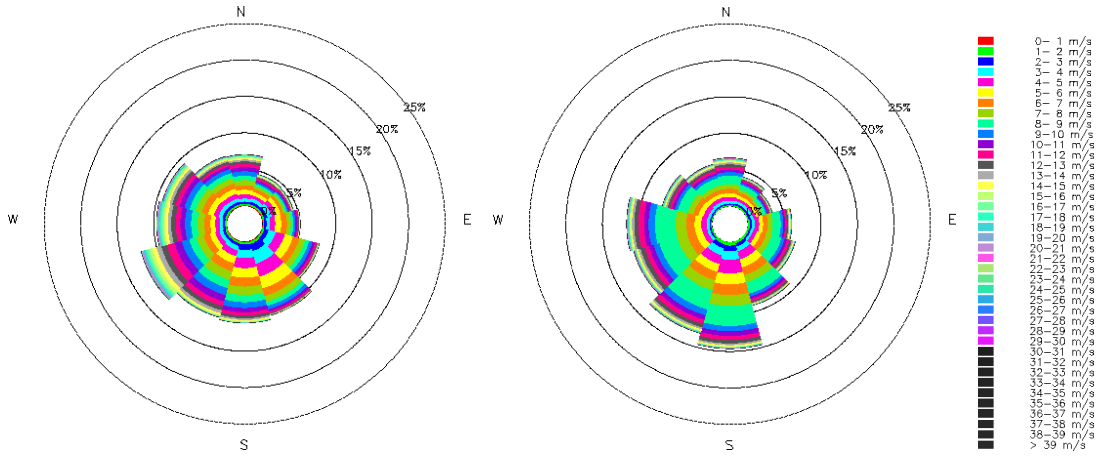

(a) Wind Atlas (b) Observations

Figure 13: **Wind roses for Malin Head at 10m agl**

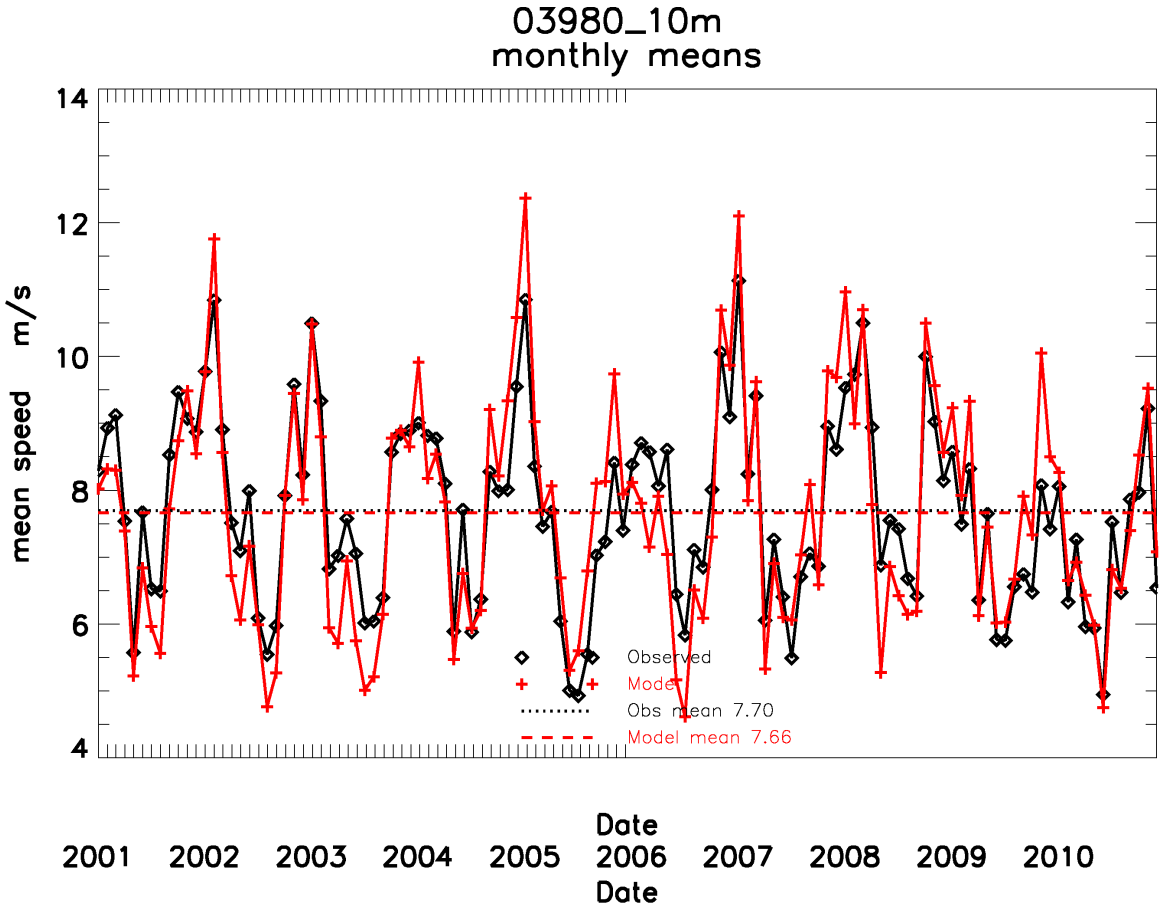

Figure 14: **Monthly mean wind speeds for the observed and wind atlas at Malin Head at 10m agl**

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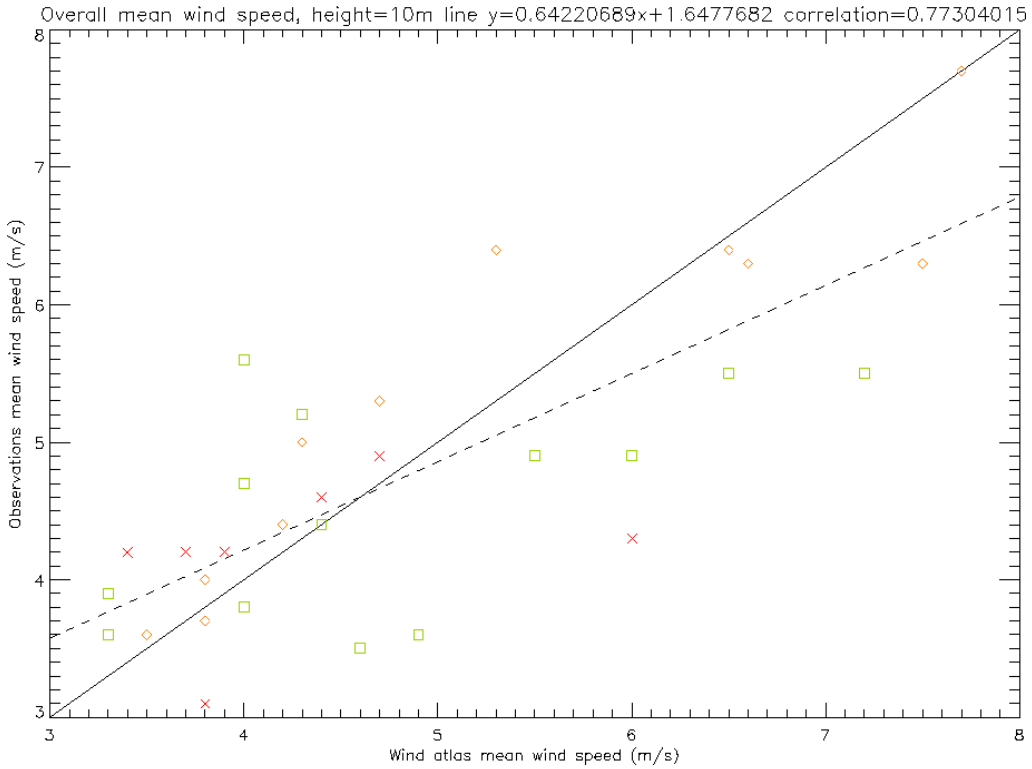

Figure 15: **Wind atlas v observed mean winds for all stations** - green are low complexity, orange are medium complexity and red are high complexity

For other locations there are greater biases, although 17 of the 32 are within 0.5 ms^{-1}, see Figure 15. The mean bias averaged over all 32 stations is 0.1 ms^{-1} and the standard deviation between the station biases is 0.8 ms^{-1} (Table 2). Therefore there is no evidence of a systematic over- or under-estimation of wind speeds generally. However, the standard deviation is somewhat larger than usual from the VMM for the low complexity locations, but very similar to VMM values at medium and high complexity locations. Several of the low complexity sites are very close to the coast or island sites and so the observed wind could reflect on-shore and sea-breeze effects. The model basis of the atlas has a resolution of 4km, so it is possible that different land/sea categorisation is effective at the coastal and island locations. Possibly a more representative comparison is with the 100m wind gridded values against the observations. The 100m values are monthly means and so are meaned over the complete months corresponding to those in the station records. Similar mean values were seen at most locations. Table 1 shows similar mean values at most locations. However at Ballypatrick Forest the excess wind speed is much reduced, and there are reduced biases at Rosslare, Gurteen, Connaught airport and Clones. Some locations have larger biases, the worst being Roches Point where a small positive bias of 0.3 ms^{-1} is -1.0 ms^{-1} from the 100m data. Generally the changes are of order 0.1 to 0.4 ms^{-1}.

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Period	Station Name	Height (m)	Observations mean (ms^{-1})	Atlas mean (ms^{-1})	Bias (ms^{-1})
01-01-2001 to 31-12-2010	St Angelo	10	4.2	3.3	-0.9
01-01-2001 to 31-12-2010	Castlederg	10	3.7	4.1	0.4
01-01-2001 to 31-12-2010	Ballykelly	10	4.7	4.0	-0.7
01-01-2001 to 31-12-2010	Lough Fea	10	4.2	3.6	-0.6
01-01-2001 to 31-12-2010	Portglenone	10	4.0	3.8	-0.2
02-01-2001 to 31-12-2010	Ballypatrick Forest	10	4.3	5.0	0.7
01-01-2001 to 31-12-2010	Aldergrove	10	4.4	4.1	-0.3
01-01-2001 to 10-11-2003	Hillsborough	10	3.6	3.5	-0.1
01-01-2001 to 31-12-2010	Glenanne No. 2	10	4.6	4.4	-0.2
01-01-2001 to 30-11-2007	Bangor Harbour	10	6.4	5.2	-1.2
19-04-2010 to 31-12-2010	Sherkin Island	10	5.5	6.5	0.9
01-01-2001 to 31-12-2010	Roches Point	10	6.3	5.3	-1.0
01-01-2001 to 31-12-2010	Valentia Observatory	10	4.9	4.4	-0.5
01-01-2001 to 31-12-2010	Cork Airport	10	5.0	4.1	-0.9
25-01-2008 to 31-12-2010	Johnstown Castle	10	3.6	4.8	1.2
01-01-2001 to 07-04-2008	Rosslare	10	5.5	6.7	1.2
01-01-2001 to 07-04-2008	Kilkenny	10	3.9	3.2	-0.7
09-06-2009 to 31-12-2010	Oak Park, Carlow	10	3.6	3.2	-0.4
01-01-2001 to 31-12-2010	Shannon Airport	10	4.9	6.0	1.1
19-04-2010 to 31-12-2010	Mace Head	10	6.4	6.5	0.1
01-01-2001 to 01-10-2009	Birr	10	3.8	4.0	0.2
19-04-2010 to 31-12-2010	Gurteen	10	3.8	3.9	0.1
01-01-2001 to 31-12-2010	Casement Airport	10	5.2	4.1	-1.2
01-01-2001 to 31-12-2010	Dublin Airport	10	5.6	4.0	-1.6
01-01-2001 to 31-12-2010	Claremorris	10	4.4	4.3	-0.1
01-01-2001 to 31-12-2010	Mullingar	10	3.5	4.6	1.1
01-01-2001 to 31-12-2010	Connaught Airport	10	4.9	5.1	0.2
01-01-2001 to 07-04-2008	Clones	10	4.2	3.7	-0.5
01-01-2001 to 31-12-2010	Belmullet	10	6.3	7.6	1.3
01-01-2001 to 31-12-2010	Finner	10	5.3	4.4	-0.9
09-06-2009 to 31-12-2010	Ballyhaise Cavan	10	3.1	3.9	0.8
01-01-2001 to 31-12-2010	Malin Head	10	7.7	7.3	-0.4

Table 1: **Comparison of synoptic station observations and modelled wind speeds at 10m from 100m data**

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Complexity	Bias	Standard Deviation
All	0.1	0.8
Low	0.2	0.9
Medium	-0.1	0.6
High	0.1	0.8

Table 2: **Mean bias and standard deviation of bias for 10m winds**

In addition to using the 10m observations to validate the 10m winds, they were also used to validate the higher elevation winds. Using the local roughness lengths as determined by the Corine land use (see Appendix A) we have derived wind speeds at height h by assuming a logarithmic neutral stability profile so that

$$w_h = \frac{w_{10} \cdot \ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{10}{z_0}\right)} \tag{7}$$

The average model-observed bias generally gets larger with elevation, ranging from 0.2 to 1.0 ms^{-1} from 20m to 150m respectively. Table 3 summarises the bias and standard deviation of the biases for the different complexity sites for heights 20m-150m agl.

Complexity	Bias	Standard Deviation
All	0.5	1.2
Low	0.8	0.9
Medium	-0.1	1.2
High	1.2	0.9

Table 3: **Mean bias and standard deviation of bias for 20m to 150m winds**

4.3 Validation Against Mast Observations

Here we compare meteorological mast observations and hourly wind values from the atlas at 13 sites with contemporary observations to the atlas period (2001-2010). The observations were kindly supplied by site operators. Gross errors in the observational records have been removed but there is scope for more extensive detailed quality control which would take more time given the volumes of data. The data were mostly supplied as 10 minute timeseries and mostly as direct data logger files. After the exclusion of gross errors a number of deficiencies and errors were corrected or removed. Mostly these related to directional errors and over-reporting of zero wind speeds (due to instruments not working). Some multi-year records have significant gaps and some have date/time errors which results in poor correlations with the hourly modelled winds. As we are concerned mostly with the long term mean winds these data/time errors have little or no affect, but should be corrected for a

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comprehensive assessment. The data providers' maintenance and monitoring reports should be accessed to correct these errors.

The sites were reasonably spread geographically and they were spread fairly evenly across the site complexity classifications.

Table 4 shows the comparison of the atlas and mast observations. For all heights other than 75m the atlas values and the observations are at the same elevations. For the 75m winds the nearest observations have been used, which are usually at 70m or 80m. The biases range from near zero to an absolute maximum error of greater than 2 ms^{-1}. The maximum absolute errors are at the lowest levels (10m) at sites 10 and 11, where the influence of local obstacles and differences between the model roughness and actual roughness will be most noticeable. Mast 12 also has a large error of -1.9 ms^{-1}. For greater altitudes the errors at these locations decrease to -1.1, -0.6 and -0.9 ms^{-1} respectively at 50m elevation. These sites are closely located geographically and so may all be affected similarly. By contrast sites 7 and 9 which are located in different regions, have smaller errors of +0.4 and -0.0 ms^{-1} at 10m agl. There is thus no indication of a systematic underestimation of wind speeds for the atlas as a whole. Again more data from several regions would help to clarify this issue. At sites 1, 2, 4, 7, 9 and 13 the biases are within 0.65 ms^{-1} at all elevations. These are of comparable accuracy to the best VMM accuracy validated at sites in the UK and Europe. The sites have been classified. Whilst 1, 7 and 9 are low complexity, 2 and 13 are medium with site 4 high complexity. By contrast the sites with larger errors are generally of medium (sites 6, 8 and 10) and high complexity (sites 5 and 12).

Using the results in Table 4, the uncertainties for different complexity have been estimated as in Table 5.

Mast No	Height (m)	Observations mean (ms^{-1})	Atlas mean (ms^{-1})	Bias (ms^{-1})
01	50	7.1	7.8	0.6
02	30	5.1	5.6	0.5
02	50	5.7	6.3	0.6
03	20	5.9	7.5	1.6
03	50	7.9	9.1	1.2
04	30	6.0	6.4	0.3
04	40	6.4	6.8	0.4
04	50	6.7	7.1	0.5
05	20	6.5	7.6	1.1
05	30	6.5	8.3	1.8
05	50	7.8	9.0	1.2
06	30	7.6	6.2	-1.4
06	40	8.0	6.7	-1.4

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06	50	8.1	7.0	-1.1
07	10	5.3	5.7	0.4
07	40	6.9	7.0	0.0
08	30	7.9	6.6	-1.2
08	50	8.6	7.5	-1.1
09	10	4.5	4.5	-0.0
09	30	5.7	6.1	0.4
09	50	6.4	6.8	0.4
09	75	6.9	7.4	0.5
10	10	5.9	3.8	-2.1
10	30	7.2	5.7	-1.5
10	40	7.4	6.2	-1.2
10	50	7.6	6.5	-1.1
11	10	6.3	4.2	-2.2
11	30	7.3	5.8	-1.5
11	40	7.8	6.3	-1.5
11	50	7.3	6.7	-0.6
12	10	6.2	4.3	-1.9
12	30	7.1	5.9	-1.2
12	40	7.3	6.4	-0.9
12	50	7.6	6.7	-0.9
13	40	6.9	6.3	-0.6
13	50	7.1	6.6	-0.5
13	75	7.4	7.2	-0.2

Table 4: **Comparison of mast observations and modelled wind speeds using matched periods**

Complexity	**Uncertainty**	
	Mean Bias (Atlas - Obs) (ms^{-1})	90th Percentile (W90) (ms^{-1})
Low Complexity	0.4	0.3
Medium Complexity	-0.2	1.4
High Complexity	-0.4	1.4
ALL SITES	-0.1	1.3

Table 5: **Estimated uncertainty values for complexity category based on 13 mast locations**

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4.4 Comparison at Small Wind Power sites

Using data from 2011 to mid 2012 from the small wind power pilot project (provided by SEAI) we have compared against the model winds from the atlas, Table 6. Vertical interpolation in log (height) has been used to derive winds at non-atlas levels. Both the horizontally interpolated winds from the 1km files and the monthly mean 100m values have been used from the atlas. Although not strictly comparable biases have been calculated. These range from +1.2 to -1.7 ms^{-1}, with smallest bias of -0.1, from the 1km data. The biases from the 100m data are generally smaller as expected.

Mast No	Height (m)	Observations mean (ms^{-1})	Atlas (1km data) mean (ms^{-1})	Bias (1km data) (ms^{-1})	Atlas (100m data) mean (ms^{-1})	Bias (100m data) (ms^{-1})
DL100	10	4.5	4.4	-0.1	4.1	-0.4
DL101	15	5.3	4.5	-0.8	4.6	-0.7
DL102	10	3.0	2.9	-0.1	3.0	0.0
DL103	10	5.1	4.0	-1.1	4.2	-0.9
DL104	15	4.1	4.5	0.4	4.4	0.3
DL105	12	4.9	4.7	-0.2	4.7	-0.2
DL106	15	4.1	4.6	0.5	4.4	0.3
DL107	15	3.9	4.2	0.3	4.1	0.2
DL108	12	3.9	5.1	1.1	5.1	1.1
DL109	10	4.8	3.3	-1.5	3.8	-1.0
DL110	12	5.7	4.0	-1.7	4.1	-1.6
DL111	15	6.0	4.9	-1.1	4.7	-1.3
DL112	15	3.7	4.9	1.2	4.9	1.2
DL113	16	5.8	5.1	-0.7	5.5	-0.3
DL114	15	4.2	5.0	0.8	5.1	0.9
DL115	30	5.6	5.8	0.2	5.8	0.2

Table 6: **Comparison of small-wind power mast observations and modelled wind speeds**

4.5 Basic Comparison with Previous Wind Atlas

Figure 16 shows a snapshot of the 50m agl onshore and offshore winds taken from the SEAI website, with the corresponding plot from the remodelled wind atlas produced in this project. They have been plotted using the same colour scale, enabling a very basic comparison between the two wind atlases. The remodelled wind atlas contains a larger offshore area than the previous wind atlas.

The wind atlases are fairly comparable, however, the remodelled wind atlas tends to have slightly

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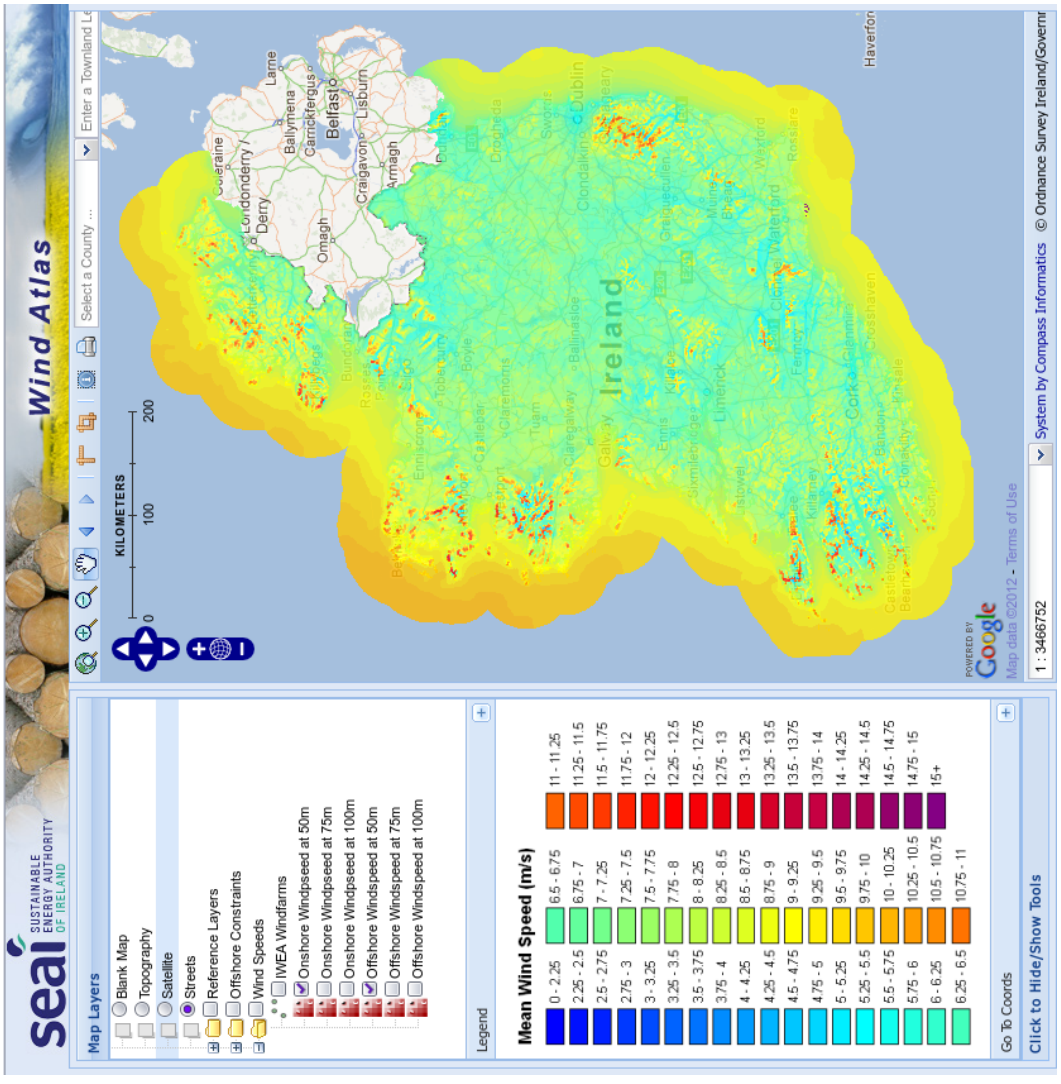
Wind Atlas
seai
SUSTAINABLE ENERGY AUTHORITY OF IRELAND
Map Layers
Blank Map
Topography
Satellite
Streets
Reference Layers
Offshore Constraints
Wind Speeds
IWEA Windfarms
Onshore Windspeed at 50m
Onshore Windspeed at 75m
Onshore Windspeed at 100m
Offshore Windspeed at 50m
Offshore Windspeed at 75m
Offshore Windspeed at 100m
Legend
Mean Wind Speed (m/s)
0 - 2.25
2.25 - 2.5
2.5 - 2.75
2.75 - 3
3 - 3.25
3.25 - 3.5
3.5 - 3.75
3.75 - 4
4 - 4.25
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6.75 - 7
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13.75 - 14
14 - 14.25
14.25 - 14.5
14.5 - 14.75
14.75 - 15
15+
Go To Coords
Click to Hide/Show Tools
Select a County ...
Enter a Townland
KILOMETERS
0
100
200
Belfast
Dublin
Ireland
Derry
Londonderry
Lisburn
Armagh
Omagh
Ballymena
Carrickfergus
Craigavon
Limerick
Galway
Cork
Waterford
Wexford
Sligo
Dundalk
Drogheda
Swords
Navan
Kilkenny
Tralee
Killarney
Ennis
Athlone
Castlebar
Roscommon
Claremorris
Ballinasloe
Tullamore
Mullingar
Portlaoise
Carlow
Wicklaw
Bray
Arklow
Enniscorthy
Wexford
Rosslare
Youghal
Dungarvan
Clonmel
Thurles
Nenagh
Ennistymon
Ennis
Shannon
Tralee
Dingle
Killorglin
Kenmare
Bantry
Skibbereen
Clonakilty
Kinsale
Cobh
Midleton
Fermoy
Mallow
Listowel
Tarbert
Kilrush
Ennistymon
Lahinch
Ballyshannon
Donegal
Letterkenny
Buncrana
Derry
Coleraine
Ballycastle
Larne
Ballymena
Carrickfergus
Lisburn
Craigavon
Armagh
Omagh
Enniskillen
Sligo
Boyle
Roscommon
Athlone
Longford
Cavan
Monaghan
Dundalk
Drogheda
Navan
Trim
Mullingar
Tullamore
Portlaoise
Kilkenny
Carlow
Wicklow
Bray
Arklow
Wexford
Rosslare
Youghal
Dungarvan
Clonmel
Thurles
Nenagh
Limerick
Ennis
Shannon
Tralee
Dingle
Killorglin
Killarney
Kenmare
Bantry
Skibbereen
Clonakilty
Kinsale
Cobh
Midleton
Fermoy
Mallow
Listowel
Tarbert
Kilrush

lower mean winds, particularly over the more sheltered areas. The previous wind atlas' core decade that it is representing is 1990-1999 whereas the remodelled wind atlas represents 2001-2010; in general the 1990s had higher winds compared to the 2000s, particularly 2010, which has mean winds of approximately 1 ms^{-1} lower than the long term average.

Similar results to those seen at 50m agl are also seen at the other levels.

4.6 Uncertainty Levels

The uncertainties of Table 5 can be used with the complexity categorisation files provided to estimate the uncertainty at any given location; the uncertainties have been derived from heights between 20 and 100m. As we have such a small sample of independent heights we make the assumption that the same values of uncertainty should be used at all heights. For example, given a location of medium complexity and mean wind of say 8 ms^{-1} we would expect a 90th percentile wind value of 8 - bias - W90, i.e. 8 - (-0.2) - 1.4 = 6.8 ms^{-1}. NB. The uncertainty levels given are subject to change in future if further high quality validation data becomes available. They should always be regarded as the latest estimate of the likely accuracy.

5 Conclusion

A remodelled wind atlas has been derived based on numerical modelling of the meteorological conditions from 2001 to 2010. The key processing used suitable local downscaling and adjustments to data from mesoscale 4km forecasts initialised from ERA-Interim reanalysis data. The atlas is provided on more vertical elevations than previously, which should help identification of suitable wind resources for smaller and intermediate-rated turbines.

In contrast to the previous atlas which was based on mesoscale model forecasts for 366 randomly sampled days over a 15 year period, the present atlas is based on a continuously modelled period of 10 years. The previous atlas documentation quotes a possible error of 3-4% due to the finite 366-day random sampling. We have carried out a sensitivity analysis by 100 realisations of a randomly selected 366-day year from the full 10 year data. The mean wind speed of the 100 realisations agrees with the full 10-year mean as expected, but there is a total spread of +/- 0.5 ms^{-1} about the mean, which is in excess of 7%. Using a standard power curve it was found that the standard deviation of the total power was 4%.

The previous atlas used the MesoMap system, and specifically the Mesoscale Atmospheric Simulation System (MASS) to downscale the NCEP/NCAR R1 reanalyses. The reanalyses were relatively coarse resolution of 250km. This remodelled atlas uses a more recently produced reanalysis, the Interim European Reanalysis which has a resolution of 80km and so provides a more accurate representation of the meteorological state as initial conditions in the construction of the atlas. The data assimilation used is a 4D variational approach which allows better treatment of

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continuously-sampled remotely-sensed observations such as satellite data. A doubly nested model was used to downscale from 80km through 12km to 4km grids. The previous map used a number of nests to downscale from 250km to 1km. Using a smaller number of nests and higher initial resolution reanalyses should improve the accuracy.

In addition to wind speed, wind direction frequencies in 30 degree bins provide information of prevailing winds. The provision of full monthly and diurnal means on a 100m grid allows seasonal and diurnal variations to be investigated and utilised in site assessments. A representative year (2006) at 1km resolution with hourly time steps allows more specific investigations to be studied. For example, investigation of the intermittency of wind on all timescales and the influence of high pressure/low wind periods.

The increased coverage offshore to 100km into the Irish Economic Zone provides information for future exploitation of the offshore wind resources.

In using the atlas users should take account of the uncertainty arising from decadal and longer period variability. Historically the 1990-2000 decade was a period with relatively high winds whilst during the decade 2001-2010 lower wind speeds occurred which were closer to the long term mean behaviour. This will be most important for assessing the viability of locations with marginal mean wind speeds.

6 Recommendations

If this work was to be repeated a number of points for further consideration are recommended:

1. Increasing the number of wind directions that the linear correction factors are calculated is likely to be beneficial. Ideally the more directions the better, however, 12 directions, which would then correspond to the binned wind directions would be beneficial.

2. The base forecast data used was at 4km resolution, using higher resolution models would be beneficial to capture more of the sub grid scale processes. As an alternative, using a shorter period of a high resolution model (at least 1 year) to regress against the coarser 4km data to provide corrections which could then be applied to the full length period supplies some of the benefits of the higher resolution model. This is currently being developed for alternative projects and replaces the requirement for the scaled roughness correction, as the higher resolution models do not contain the orographic drag scheme.

3. The wind atlas is designed to be representative of the years 2001-2010 inclusive, however, in order to fully capture climate variability a much longer period would need to be used, for example the whole of the ERA-Interim period (1979-present) or even longer. This is computaitonally expensive, however the Met Office has now generated a hindcast data set produced in a similar way to that used for this project at 4.4km resolution over the whole of Europe, which could be used to generate a wind atlas in a similar way.

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4. Obtaining high quality verification data at heights above 10m has proved difficult and timely. This has severely affected our ability to provide high quality verification of the data set. For any future wind atlases produced, agreements ahead of time with the data holders of such records would be vital.

5. In addition to the limited observations over land, we have been unable to verify any offshore points due to having no observations at any offshore sites.

6. This work has revealed there are still problems with reversal of wind profiles and high winds at the coast which need further attention. Higher resolution CFD models are more suitable for complex cases such as this.

7 Acknowledgements

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A Processing of Corine

Both of the correction procedures used to adjust the winds to produce the Irish wind atlas require details on the roughness length (z_0) and for the roughness correction it also requires the displacement height (d). The land use classification was taken from the Corine land cover data set at 100m resolution. Further details on Corine can be found in European Environment Agency (2007).

To use the Corine land cover classes typical surface roughness lengths and displacement heights need to be assigned. A number of different approaches were reviewed. The previous atlas (see Appendix F of Brower et al. (2003)) assigned roughnesses to the 44 land use classes. We have also chosen this approach and the values used are given in Table A.1. The recent Finnish Wind Atlas used fewer classes (Tammelin et al. 2012) as did Silva et al. (2007), who combined some classes into 14 roughness classes. We were guided by these and by the approach used previously in a Met Office study for the Carbon Trust (Best et al. 2008) and earlier published roughness values of the European Wind Atlas (Troen and Petersen 1989).

The values of roughness, z_0, and displacement height, d, were based on those used in the Carbon Trust report and standard MetUM values. Displacement heights were limited to $7.0m$ for trees and urban fabric. The height for trees may be less representative in continuous forests. Smaller trees and orchards were assigned $d = 1.0$ and $z_0 = 0.3m$. Pastures, agricultural crops and natural grasslands and heaths were all assigned the same roughness of $0.14m$, the standard MetUM value. Shrub land is rougher with $z_0 = 0.18$. For continuous and discontinuous urban fabric, the roughness values are larger than the previous atlas which used 1.0 and $0.5m$, but is similar to the Finnish atlas values of 1.5 and $0.6m$ whilst Silva et al estimates between $1.1-1.3$ and $0.5m$. The open water value of $z_0 = 10^{-4}$ is the same as used in the previous atlas, but is smaller than the standard MetUM value of $3 \cdot 10^{-4}$, though the wind speed over land will not be sensitive to this.

In general the roughness values used here are larger than those of the previous atlas and so would lead to generally lower wind speeds.

Plots of the values assigned over the domain can be seen in Figure A.1.

Number	Description	Roughness Length z_0 (m)	Displacement Height d (m)
1	111 Continuous urban fabric	1.6	7.0
2	112 Discontinuous urban fabric	0.7	3.1
3	121 Industrial or commercial units	0.7	3.1
4	122 Road and rail networks and associated land	0.1	0.0
5	123 Port areas	0.3	0.0
6	124 Airports	0.03	0.0
7	131 Mineral extraction sites	0.1	0.0
8	132 Dump sites	0.1	0.0

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Table A.1 – *Continued from previous page*			
Number	**Description**	**Roughness Length z_0 (m)**	**Displacement Height d (m)**
9	133 Construction sites	0.3	0.0
10	141 Green urban areas	0.4	0.0
11	142 Sport and leisure facilities	0.5	0.0
12	211 Non-irrigated arable land	0.03	0.0
13	212 Permanently irrigated land	0.03	0.0
14	213 Rice fields	0.03	0.0
15	221 Vineyards	0.3	1.0
16	222 Fruit trees and berry plantations	0.3	1.0
17	223 Olive groves	0.3	1.0
18	231 Pastures	0.14	0.0
19	241 Annual crops associated with permanent crops	0.14	0.0
20	242 Complex cultivation patterns	0.14	0.0
21	243 Land principally occupied by agriculture, with significant areas of natural vegetation	0.18	0.0
22	244 Agro-forestry areas	1.0	7.0
23	311 Broad-leaved forest	1.0	7.0
24	312 Coniferous forest	1.0	7.0
25	313 Mixed forest	1.0	7.0
26	321 Natural grasslands	0.14	0.0
27	322 Moors and heathland	0.14	0.0
28	323 Sclerophyllous vegetation	0.18	0.0
29	324 Transitional woodland-shrub	0.5	3.5
30	331 Beaches, dunes, sands	0.0003	0.0
31	332 Bare rocks	0.003	0.0
32	333 Sparsely vegetated areas	0.02	0.0
33	334 Burnt areas	0.001	0.0
34	335 Glaciers and perpetual snow	0.0001	0.0
35	411 Inland marshes	0.03	0.0
36	412 Peat bogs	0.03	0.0
37	421 Salt marshes	0.003	0.0
38	422 Salines	0.003	0.0
39	423 Intertidal flats	0.003	0.0

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Table A.1 – *Continued from previous page*			
Number	**Description**	**Roughness Length z_0 (m)**	**Displacement Height d (m)**
40	511 Water courses	0.0001	0.0
41	512 Water bodies	0.0001	0.0
42	521 Coastal lagoons	0.0001	0.0
43	522 Estuaries	0.0001	0.0
44	523 Sea and ocean	0.0001	0.0

Table A.1: **Roughness length and displacement height assigned to each land use class in the Corine land use dataset**

A grid box average for z_0 and d are calculated for the 1km grid as follows:

1. Land fractions, F_i for each of the Corine classes are derived for the 100m Corine data set.

2. Using a blending height, l_b of 20m the average effective roughness and displacement heights are given by

$$\left[\ln\left(\frac{l_b - d_{eff}}{z_{0_eff}}\right)\right]^{-2} = \sum_{i=\text{land classes}} F_i \left[\ln\left(\frac{l_b - d_i}{z_{0_i}}\right)\right]^{-2} \tag{8}$$

   where $d_{eff} = \max(d_i)$ for d_i with non zero F_i.

   The blending height, l_b, is the height below which the local wind profile can be treated as in equilibrium with the local surface roughness and above which the *area-average* profile is in equilibrium with the effective *area-average* surface roughness.

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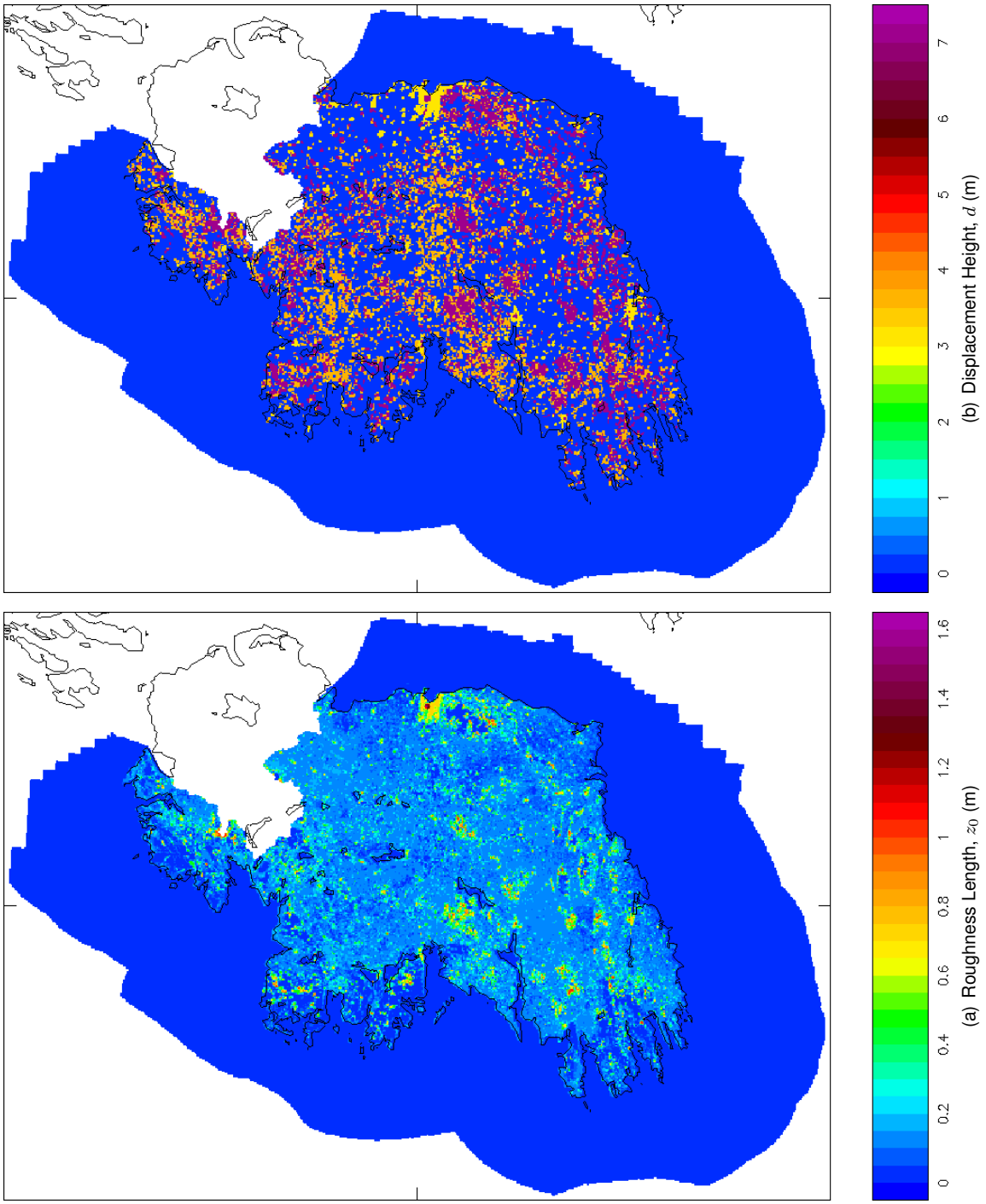

Figure A.1: **Values of the roughness length and displacement height assigned to the Corine land use dataset** - on the 1km rotated pole grid

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